Percolated water can leach undesirable chemical compounds below the rooting zone of plants and into drainage water or through the vadose zone into the groundwater. Even though the ocean serves as a huge sink for salts and pollutants, the contamination of streams, rivers, lakes, and groundwater resources poses a great threat to plant and animal health, the environment, the economy, and civilization.

Further Reading

Berner EK and Berner RA (1996) *Global Environment: Water, Air, and Geochemical Cycles*. Upper Saddle River, NJ: Prentice-Hall.

Browning KA and Gurney RJ (1999) *Global Energy and Water Cycles*. Cambridge, UK: Cambridge University Press.

Carpenter SR, Fisher SG, Grimm NB, and Kitchell JF (1992) Global change and freshwater ecosystems. *Annual Review of Ecology and Systematics* 23: 119–139.

Gleick PH (1993) An introduction to global fresh water issues. In: Gleick PH (ed.) *Water in Crisis: A Guide to the World's Fresh Water Resources*, pp. 3–12. New York: Oxford University Press.

Guymon GL (1994) *Unsaturated Zone Hydrology*. Englewood Cliffs, NJ: Prentice-Hall.

Hillel D (1998) *Environmental Soil Physics*. San Diego, CA: Academic Press.

Howells G (1995) *Acid Rain and Acid Waters*, 2nd edn. New York: Ellis Harwood.

Postel S (1999) *Pillar of Sand: Can the Miracle Last?* Saddle Brook, NJ: WW Norton.

Vorosmarty CJ, Green P, Salisbury J, and Lammers RB (2000) Global water resources: vulnerability from climate change and population growth. *Science* 289: 284–288.

Wetzel RG (1983) *Limnology*, 2nd edn. New York: Saunders College.

Water Erosion *See* **Erosion:** Water-Induced

WATER HARVESTING

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Definition

The term 'water harvesting' generally refers to the collection of rainstorm-generated runoff from a particular area (a catchment) in order to provide water for human, animal, or crop use. The water thus collected can either be utilized immediately, as for irrigation, or be stored in aboveground ponds or in subsurface reservoirs, such as cisterns or shallow aquifers, for subsequent utilization. As such, water harvesting is an ancient practice that has enabled some societies to subsist in semiarid and arid areas where other sources of fresh water (e.g., rivers, lakes, or aquifers) are scant or unavailable.

Surface Runoff

Whenever the rate at which rainwater is applied to the soil surface exceeds the rate of infiltration into the soil, the excess tends to accumulate over the surface. Where the surface is not perfectly flat and smooth, the excess water collects in depressions, forming puddles. The total volume of water thus held, per unit area, is called 'surface-storage capacity.' It depends on the geometric irregularities (roughness) of the surface as well as on the overall slope of the land (Figure 1).

Only when the surface storage is filled and the puddles begin to overflow can actual runoff begin. The term 'surface runoff' thus represents the portion of the water supply to the surface that is neither absorbed by the soil nor accumulates on its surface, but that runs downslope.

Surface runoff typically begins as sheet flow but, as it accelerates and gains in erosive power, it eventually scours the soil surface to create channels. There exists

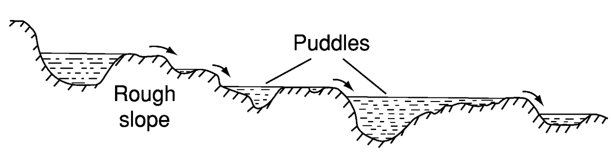

Figure 1 Effect of surface roughness and slope on surface storage of rainfall excess. Reprinted from *Environmental Soil Physics*, Hillel D (ed.). Copyright (1998), with permission from Elsevier.

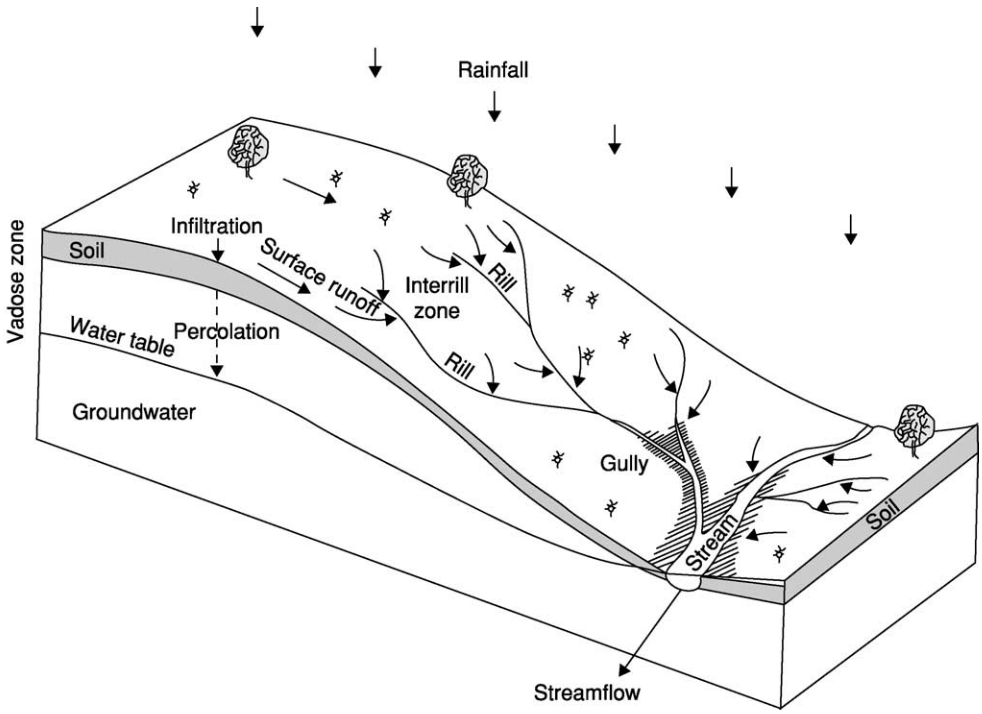

Figure 2 A sloping area exhibiting overland flow as well as runoff through rills and gullies. Reprinted from *Environmental Soil Physics*, Hillel D (ed.). Copyright (1998), with permission from Elsevier.

a wide spectrum of channel geometries and flow patterns. On the one extreme is the thin, sheet-like runoff called 'overland flow.' It is likely to be the primary form of surface runoff from small areas or fields having little topographic relief. The next distinctive form of flow takes place in small channels called rills. The latter gather the overland flow in a continuous fashion along their length to form the lowest order of stream flow. As these small streamlets merge with one another, they form higher-order channels, called gullies, which collect concentrated tributaries as well as distributed (lateral) overland flows (Figure 2).

Runoff Control and Utilization

Uncontrolled runoff is never desirable, as it is likely to cause soil erosion on slopes as well as flooding and silting in bottomlands. In humid regions, where rainfall may be excessive, measures may be needed to ensure the safe routing and conveyance of the runoff. Such measures, called 'surface drainage,' include shaping the land and treating it so as to direct the runoff via protected (grassed or even concrete-lined) channels. In semiarid regions, by way of contrast, natural rainfall is barely sufficient for crops, hence farmers typically strive – by such means as terracing and mulching – to cause as much of the rainfall as possible to infiltrate the soil, and thereby to minimize runoff.

The situation is fundamentally different in arid (as distinct from semiarid) regions. In many arid regions, large tracts of land are basically unsuitable for conventional rainfed farming, owing to the paucity and instability of rainfall, the nature of the soil (too shallow, stony, or saline to permit cultivation), or the rough topography. From the point of view of farmers (though not of ecologists, who are concerned about an area's natural biota rather than about crop production per se), rain falling on such lands is almost totally lost – being insufficient either to recharge groundwater or to support an economically viable crop.

Most of the meager rainwater generally infiltrates the soil to a shallow depth only, and it is quickly returned to the atmosphere – either by direct evaporation from the soil or by transpiration from native vegetation. Occasional intense rainstorms may none the less generate runoff and cause sudden flash floods. Although runoff from any particular rainstorm may be high, under natural conditions the total seasonal runoff seldom exceeds 10% of the annual precipitation.

The possibility of controlling and even increasing the amount of surface runoff obtainable from such lands can be of great importance. Particularly where no other dependable water source is available, the runoff thus obtained may constitute the major supply of an inhabited area.

Ancient Methods

The art of inducing, collecting, and utilizing runoff has been practiced by desert-dwelling communities since antiquity, in such disparate regions as southwestern Asia, northern Africa, and southwestern North America. Remnants of extensive water-harvesting systems are found in these regions.

Highly noteworthy are the works of the ancient Nabateans, who inhabited the Negev Desert of southern Israel some 2000 years ago. They began as caravan drivers, conveying aromatic, spicy, and medicinal plant-products, as well as other precious objects of trade, from distant sources across the desert to the major population centers along the shores of the Mediterranean Sea. The Nabateans established stations along their trading routes, and these grew in time into permanent settlements and even into cities. To sustain their population in the desert environment, the Nabateans built extensive terraces and channels, and hewed out numerous cisterns. Remains of their cities (most notable among them being the city of Petra, in southern Jordan) can be visited today.

The first imperative of desert settlement was the provision of potable water for humans and livestock. This was done by means of cisterns, which are artificially constructed reservoirs filled with surface flows during infrequent rains. The early cisterns were undoubtedly leaky and inefficient. Building efficient cisterns became possible only with the advent of watertight plaster, made of burned and slaked lime. Also crucial was the ability to recognize suitable rock formations, such as soft marly chalk, which could be hewed out readily and was not as fissured and leaky as the hard limestone that is also prevalent in the same region. The Nabateans were also skilled at choosing appropriate sites for their cisterns and at ensuring that they could be filled with water annually.

Where cisterns could be located alongside natural streams, they were filled directly by flash floods. However, most cisterns in the Negev were built along the lower reaches of hillsides and depended on the direct collection of runoff from the higher slopes. Many hundreds of such cisterns were built in the Negev, and they are clearly discernible landmarks even today. A typical one resembles a giant necklace, with the glistening white pile of excavated rock appearing to hang like a pendant from the two collection channels that ring the hill and curve down its sides from opposite directions (Figure 3). To parched travelers through the desert, to whom these cisterns would beckon from afar, no sight could be more gladdening.

The application of water-harvesting techniques to enable farming in desert areas (that is to say, collecting runoff from sloping areas and using it to irrigate plots or tracts of flat land, where crops could be grown) has been called 'runoff farming.' In ancient times, stone dikes were constructed across tributary streambeds, thus forming a series of terraced fields. These fields were watered by flows arriving from the upper watershed of the stream, as well as from the adjacent hillslopes. The slopes were often divided into sections, the runoff from each of which was led by means of constructed channels to specific fields (Figure 4). The water retained and infiltrated in each field was then utilized by annual crops (e.g., wheat or barley) or by perennial crops (e.g., grapevines, olive trees, or other fruit trees).

Water Spreading

Another form of water harvesting, called 'water spreading,' consists of diverting flash floods from intermittent streams (known as *wadis* in the Middle East, *arroyos* in the American Southwest, and *dongas* in parts of Africa) on to adjacent tracts of land. It is a simple form of flood irrigation, controlled by dikes, check dams, or channels designed to direct and spread the expected flow. It is generally used to irrigate pastures and rangelands, but in places also to sustain groves of trees in arid areas.

Water spreading is typically practiced on small watersheds of a few square kilometers. In larger watersheds, the floods may occasionally be too violent or torrential to be controlled by simple diversion structures. In such cases, a more complex system may be required: the construction of dams designed not to retain the floods but merely to detain and regulate them, so as to provide farm units located downstream from the dam with controlled flows. Such dams, called 'detention dams,' are built across a stream in order temporarily to impound the flood. A large-diameter open pipe is laid through the dam to permit downstream flow at a predetermined rate, as through the drain of a bathtub. Thus, a flash flood that would normally last just a few hours is made to flow through the pipe and on to a series of fields for perhaps several days. The field dikes (made of compacted earth or stone) can then be built economically and safely to withstand floods of a known maximal intensity, so farming operations can be planned accordingly (Figure 5).

Runoff Inducement

The builders of runoff utilization systems in the Negev in ancient times had to contend with the paucity of natural runoff, and there is evidence that they actually strove to augment it. They developed techniques for inducing a greater portion of the rainfall to trickle downslope as runoff.

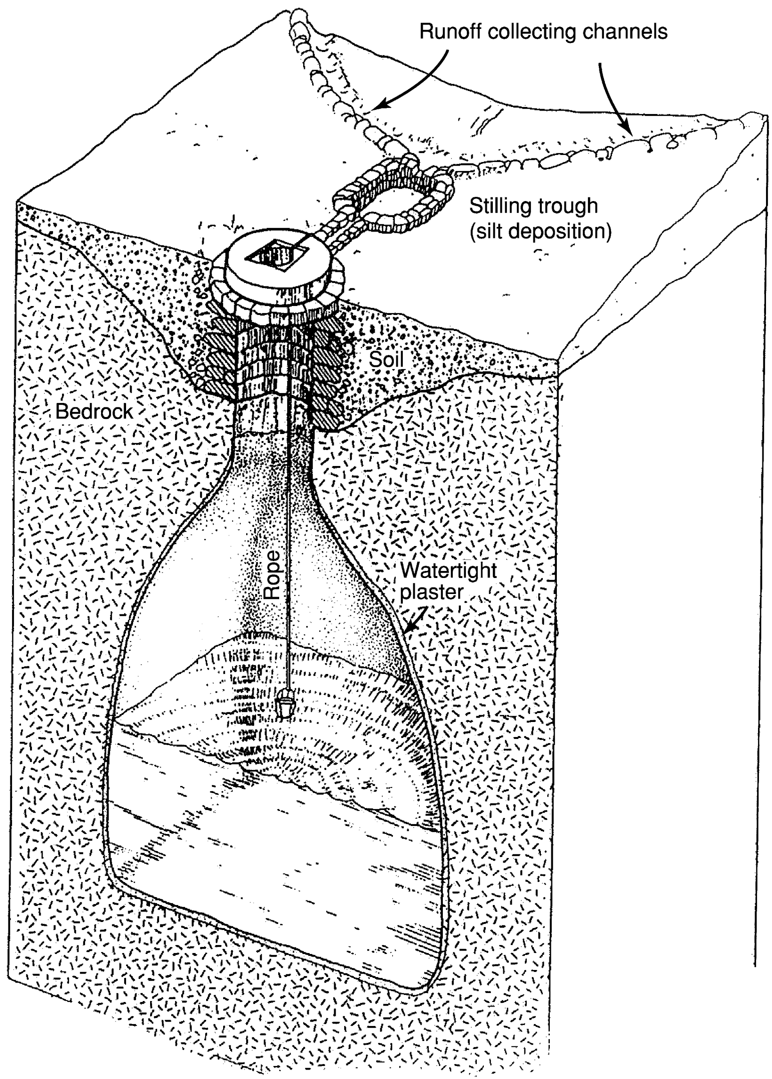

Figure 3 A typical hillside cistern excavated in the bedrock and filled by runoff from a sloping catchment. Reproduced from Hillel D (1982) *Negev: Land, Water, and Life in a Desert Environment*. New York: Praeger Publishers. © D Hillel.

Noticing that the soil had a natural tendency to crust, which was obstructed, however, by the desert's natural cover of loose gravel (commonly known as 'desert pavement'), the ancient inhabitants of the Negev region in southern Israel raked the stones off the surface in order to expose the finer soil material and to induce the formation of a surface seal. Even so, the ancient runoff farmers needed a water-contributing area approximately 20 times larger than the area to which water was directed for crop production. Similar techniques were used to collect runoff in cisterns for subsequent use as drinking water for humans and domestic animals (goats, sheep, and camels).

The importance of runoff inducement is greater than the mere increase in runoff yield that it may produce. The practice can also lower the 'runoff threshold' of a rainstorm, i.e., the minimal rainstorm (in terms of intensity, duration, and total amount of rain) needed to initiate runoff. This decrease in the threshold correspondingly increases the probability of obtaining runoff a sufficient number of times during the season to provide for the needs of domestic human use, as well as for agricultural or industrial purposes. This is especially important in view of the fact that most of the storms in an arid region result in light rains only, and that only a few storms (typically no more than two or three per season) are of sufficient intensity and quantity to yield runoff under natural conditions.

Still another climatic feature of arid regions that adds to the importance of runoff inducement is the interannual variability of rainfall. Most years provide less than the average (or mean) rainfall, and only a few anomalously rainy years skew the mean. (In statistical terms, mode and median rainfall tend to be less than the long-term mean rainfall.) In such regions, droughts are relatively frequent and may be very severe. In some years, there may be practically no

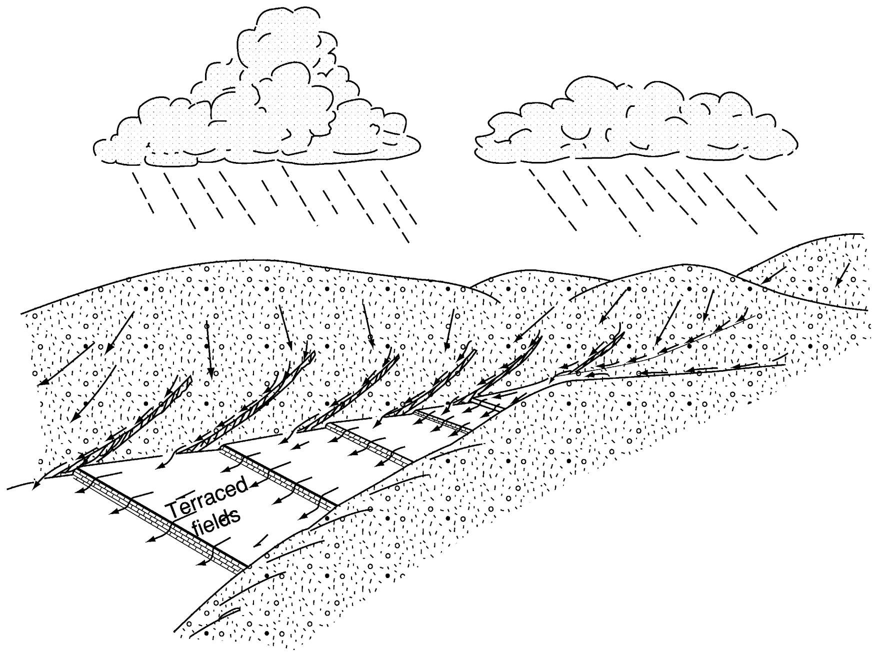

Figure 4 Ancient runoff farming in the Negev: water trickling off barren slopes was directed to terraced fields in the *wadi* bed. Reprinted from *Environmental Soil Physics*, Hillel D (ed.). Copyright (1998), with permission from Elsevier.

intense rainstorms and therefore no substantial natural runoff. Human enterprises dependent on the collection and utilization of runoff must therefore ensure, first of all, that there be a minimally sufficient water supply even in years of drought. Methods of runoff inducement can greatly contribute to this end.

Modern Methods

Modern technology holds the promise of more efficient runoff inducement than was possible in ancient times. The simplest, though generally most expensive, way to induce runoff is to cover the surface with an impervious apron of such materials as plastic, rubber, or aluminum sheeting, or by asphalt or concrete paving. A possibly more economical approach is to cause the soil itself to shed, rather than absorb, the rain. Runoff from natural surfaces can be increased several-fold by means of mechanical treatments (stone clearing, smoothing, and compaction), as well as by a variety of chemical treatments to encrust and stabilize the surface so as to prevent erosion of the runoff-contributing areas. Accordingly, the soil surface can be made water-repellent and relatively impermeable by treating it with sprayable clay-dispersants, sealers, and hydrophobic agents. The following series of treatments can be applied:

1. Eradication of vegetation and removal of surface stones, to reduce interception of rain and obstruction of overland flow, and to permit the formation of a continuous surface crust;
2. Smoothing of land surface, to obliterate surface depressions and prevent the retention of water in puddles;
3. Compaction of the soil top-layer to reduce its permeability. This can be done by means of a roller at optimal soil moisture content;
4. Dispersion of soil colloids to cause crusting, by means of sprayable solutions of sodic salts. This treatment pertains to soils that contain sufficient clay to be dispersible, but not so much as to exhibit marked shrinkage and cracking;
5. Impregnation of the surface with a sealing and binding substance such as an emulsion of asphalt that can form a water-repellent and stable coating.

With such methods, it is possible not only to increase the total yield per unit area of the watershed, but also to decrease the threshold of rain needed to form runoff and thus to increase the frequency of runoff supply and contribute to the efficiency and economic feasibility of agricultural and engineering systems designed to utilize runoff. In a desert with a seasonal rainfall of 250 mm, for instance, yields as high as 200 000 m^3 of water may be obtainable per square kilometer of treated area per season.

Several systems have been tried with respect to the size and arrangement of the contributing area in relation to water-receiving areas or reservoirs. A small watershed may be treated in its entirety so as to provide the maximal amount of water at the outflow

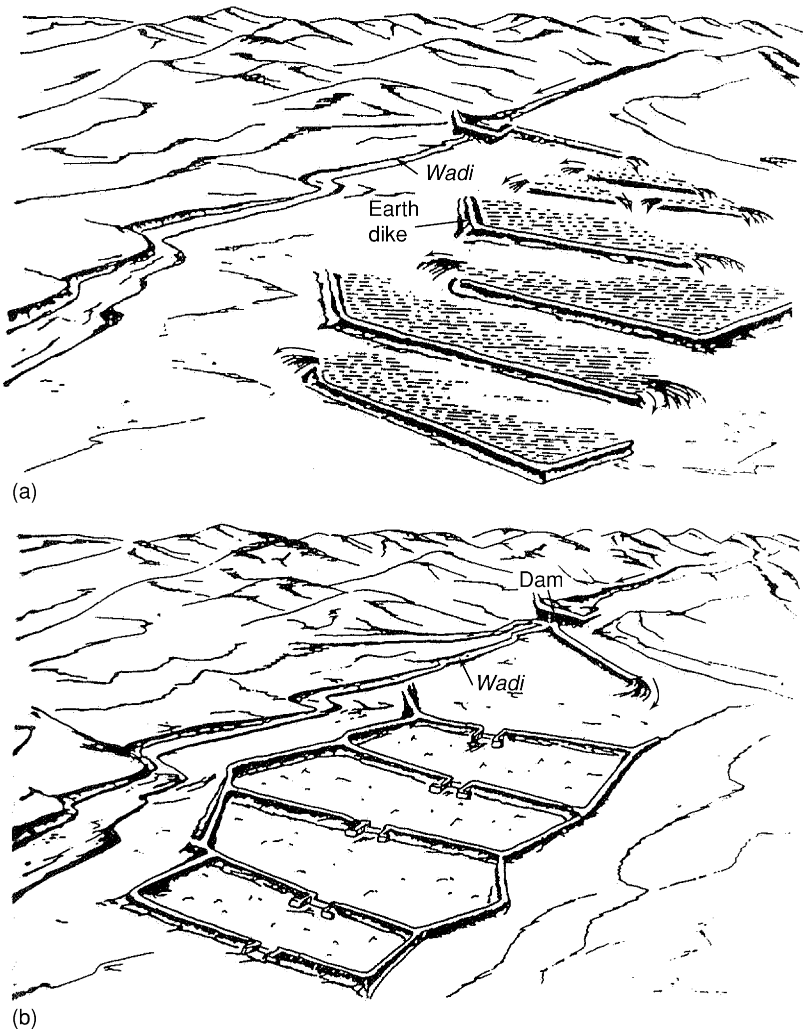

Figure 5 Two general methods of water spreading by diversion from an intermittent stream (a *wadi*) on to adjacent land: (a) diversion of an uncontrolled flow over unleveled land by means of a zigzag series of earthen dikes; and (b) diversion of a controlled flow from a detention dam to a series of level basins with concrete- or stone-lined spillways. Reproduced from Hillel D (1982) *Negev: Land, Water, and Life in a Desert Environment*. New York: Praeger Publishers. © D Hillel.

of the basin for conveyance to a pond or a series of irrigated fields. Another system of runoff farming may consist of strips treated to shed runoff, alternating with basins or areas treated to receive and absorb the runoff (Figure 6). A third possibility is to form microwatersheds, wherein each contributing area serves a single tree or row of plants.

In the ancient runoff-farming systems found in the Negev of Israel, the measured ratio of runoff-contributing areas to the runoff-receiving areas is generally between 30:1 and 20:1. In a region with a mean annual rainfall of 100 mm and a mean runoff yield of 10%, a 'runoff-to-runon' area ratio of 10:1 would double the effective water supply to an agricultural plot, a 20:1 area ratio would triple it, and a 30:1 ratio would quadruple it. The latter ratio would provide 400 mm (100 mm of rain plus 300 mm of runon) to a plot of arable land that would otherwise receive only 100 mm. (These data are hypothetical.) If using methods of runoff inducement can increase the mean runoff yield to approximately 50%, then the runoff-to-runon area ratio may be reduced to about

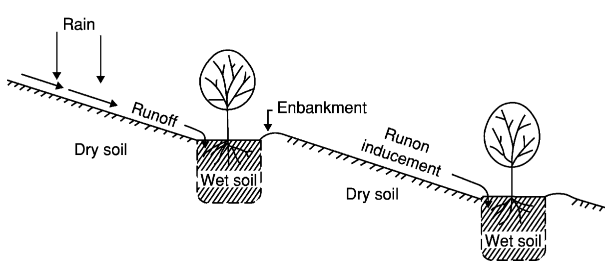

Figure 6 Schematic of a modern runoff-farming system. Reprinted from *Environmental Soil Physics*, Hillel D (ed.). Copyright (1998), with permission from Elsevier.

6:1 or even less. Moreover, the number of months or seasons without a minimally sufficient water supply (owing to the paucity of rain during a drought) would diminish and the entire system could thereby operate with a greater probability of success.

See also: **Infiltration**; **Overland Flow**

Further Reading

Bruins HM, Evenari M, and Nessler U (1986) Rainwater-harvesting agriculture for food production in arid zones. *Applied Geography* 6: 13–33.

Critchey W and Siegert K (1991) *Water Harvesting Manual.* Rome: Food and Agriculture Organization.

Dutt GR, Hutchinson CF, and Anaya Garduno M (eds) (1981) *Rainfall Collection for Agriculture in Arid and Semiarid Regions.* Farnham Royal, UK: Commonwealth Agricultural Bureaux.

Evenari M, Shanan L, and Tadmor N (1971) *The Negev: The Challenge of a Desert.* Cambridge, MA: Harvard University Press.

Hillel D (1982) *Negev: Land, Water, and Life in a Desert Environment.* New York: Praeger Publishers.

Hillel D (1994) *Rivers of Eden: The Struggle for Water and the Quest for Peace in the Middle East.* New York: Oxford University Press.

Water Management *See* **Crop Water Requirements**

WATER POTENTIAL

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Introduction

Water status in soils is characterized by both the amount of water present and its energy state. Soil water is subjected to forces of variable origin and intensity, thereby acquiring different quantities and forms of energy. The two primary forms of energy of interest here are kinetic and potential. Kinetic energy is acquired by virtue of motion and is proportional to velocity squared. However, because the movement of water in soils is relatively slow (usually less than 0.1 m h^{-1}) its kinetic energy is negligible. Potential energy, which is defined by the position of soil water within a soil body and by internal conditions, is largely responsible for determining soil water status under isothermal conditions.

Like all other matter, soil water tends to move from where the potential energy is higher to where it is lower, in pursuit of equilibrium with its surroundings. The magnitude of the driving force behind such spontaneous motion is a difference in potential energy across a distance between two points of interest. At a macroscopic scale, we can define potential energy relative to a reference state. The standard state for soil water is defined as pure and free water (no solutes and no external forces other than gravity) at a reference pressure, temperature, and elevation, and is arbitrarily given the value of zero.

The 'Total' Soil Water Potential and its Components

Soil water is subject to several force fields, the combined effects of which result in a deviation in potential energy relative to the reference state, called the 'total soil water potential' (ψ_T) defined as: "The amount of work that an infinitesimal unit quantity of water at equilibrium is capable of doing when it moves (isothermally and reversibly) to a pool of water at similar standard (reference) state, i.e., similar pressure, elevation, temperature and chemical composition." It should be emphasized that there are alternative definitions of soil water potential using concepts of chemical potential or specific free energy of the chemical species water (which is different from the soil solution termed 'soil water'). Recognizing that these fundamental concepts are subject to ongoing debate, presented here are simple and widely accepted definitions which are applicable at macroscopic scales and which yield an appropriate framework for practical applications.

The primary forces acting on soil water held within a rigid soil matrix under isothermal conditions can be conveniently grouped as: (1) matric forces